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Emplacement of inflated Pāhoehoe flows in the Naude's Nek Pass, Lesotho remnant, Karoo continental flood basalt province: use of flow-lobe tumuli in understanding flood basalt emplacement

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Abstract

Physical volcanological features are presented for a 710-m-thick section, of the Naude's Nek Pass, within the lower part of the Lesotho remnant of the Karoo Large Igneous Province. The section consists of inflated pāhoehoe lava with thin, impersistent sedimentary interbeds towards the base. There are seven discreet packages of compound and hummocky pāhoehoe lobes containing flow-lobe tumuli, making up approximately 50% of the section. Approximately 45% of the sequence consists of 14 sheet lobes, between 10 and 52-m-thick. The majority of the sheet lobes are in two packages indicating prolonged periods of lava supply capable of producing thick sheet lobes. The other sheet lobes are as individual lobes or pairs, within compound flows, suggesting brief increases in lava supply rate. We suggest, contrary to current belief, that there is no evidence that compound flows are proximal to source and sheet lobes (simple flows) are distal to source and we propose that the presence of flow-lobe tumuli in compound flows could be an indicator that a flow is distal to source. We use detailed, previously published, studies of the Thakurvadi Formation (Deccan Traps) as an example. We show that the length of a lobe and therefore the sections that are 'medial or distal to source' are specific to each individual lobe and are dependent on the lava supply of each eruptive event, and as such flow lobe tumuli can be used as an indicator of relative distance from source.

Keywords Karoo · Tumuli · Hummocky pāhoehoe · Continental flood basalt · Naude's Nek · Horizontal vesicular sheets · Deccan · Thakurvadi

Introduction

Continental flood basalt (CFB) sequences, especially the giant Mesozoic provinces such as Siberia (e.g. Sharma 1997;

Reichow et al. 2005; Saunders and Reichow 2009), Central Atlantic Magmatic Province (e.g. Knight et al. 2004; El Hachimi et al. 2011), Karoo-Ferrar (e.g. Marsh et al. 1997; Duncan and Marsh 2006), Paraná-Etendeka (e.g. Peate 1997; Waichel et al. 2006; Rossetti et al. 2017) and Deccan (e.g. Beane et al. 1986; Walker 1999), are manifestations of continental mafic magmatism of a scale unknown in modern volcanic systems. They are characterised by subaerial emplacement of very large volumes of basaltic lava flows, dominantly pāhoehoe (e.g. Bryan et al. 2010; Self et al. 2015), in thick packages spread over areas frequently in excess of a 1×10^6 km² (Self et al. 2015), with very short time spans of emplacement (~1 Ma; Bryan et al. 2010). They present challenges to understanding the sources of their magmas, temporal and spatial relationship to supercontinents (Svensen et al. 2017), continental rifting and possible mantle plumes (Burke and Torsvik 2004; Ernst and Bleeker 2010), magma supply and distribution systems such as dyke and sill complexes, and not least lava flow emplacement and lava pile construction (Walker 1971; Jay et al. 2009). The latter is important and

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raises a number of questions. How, in a short space of time, does one inundate 1×10^6 km² or more of continental surface areas with lava (Thordarson and Self 1998)? Are the emplacement mechanisms inferred from young, small-volume systems applicable (e.g. Bondre and Hart 2008; Bondre et al. 2004; Sheth 2006)? If so, what are the implications for vent distribution and magma supply? Whether such inferences are valid requires detailed observations of the lava flow features of the older CFBs and careful comparison with the modern systems (Thordarson and Self 1998). One issue facing such comparisons is the fact that in the older lava sequences observations are usually confined to two dimensions whereas in modern systems observations relating to three spatial dimensions are usually possible. If we take the modern analogue to hold true, is it possible to use observations of features in modern three-dimensional volcanic fields to understand the relative location of a two-dimensional CFBP outcrop within its flow field and hence provide a better understanding of the growth and development of the CFBP as a whole.

This paper provides the first documentation of the physical volcanology of the Lesotho remnant of the Karoo (Fig. 1) continental flood basalt province (CFBP). It is temporally linked to the second-order mass extinction events at the Pliensbachian-Toarcian boundary and the early Toarcian and coeval environmental perturbations (Wignall 2001; Wignall and Bond 2008). We provide a description of the field area and of the physical volcanological features found along the Naude's Nek section. These are described from oldest to youngest.

We focus on lava flow morphology and characteristics and, in particular, the preservation of flow-lobe tumuli in some of the flows, and discuss these observations in the context of other CFBPs.

Thordarson and Self (1998) state that volcanological features 'scale up' from modern Hawaiian scales to those found in CFBPs, in that the same features at different scale are caused by the same processes. We use this fact to discuss what the presence or absence of flow-lobe tumuli in a CFBP can tell us about the emplacement rate of pāhoehoe flows in CFBPs and how they can be used to qualitatively assess the relative position of a flow from its source. We also aim to disprove the statement that the presence of compound flows is indicative of proximity to source (Deshmukh 1988; Viereck et al. 1988; Leshner et al. 1999; El Hachimi et al. 2011), and suggest that flow-lobe tumuli can be used to indicate that a flow is medial or distal to source.

Geological setting

The Karoo CFBP is dominated by tholeiitic basaltic lavas which currently occur in erosional remnants scattered across 2×10^6 km² in southern Africa (Cox 1970). The Lesotho

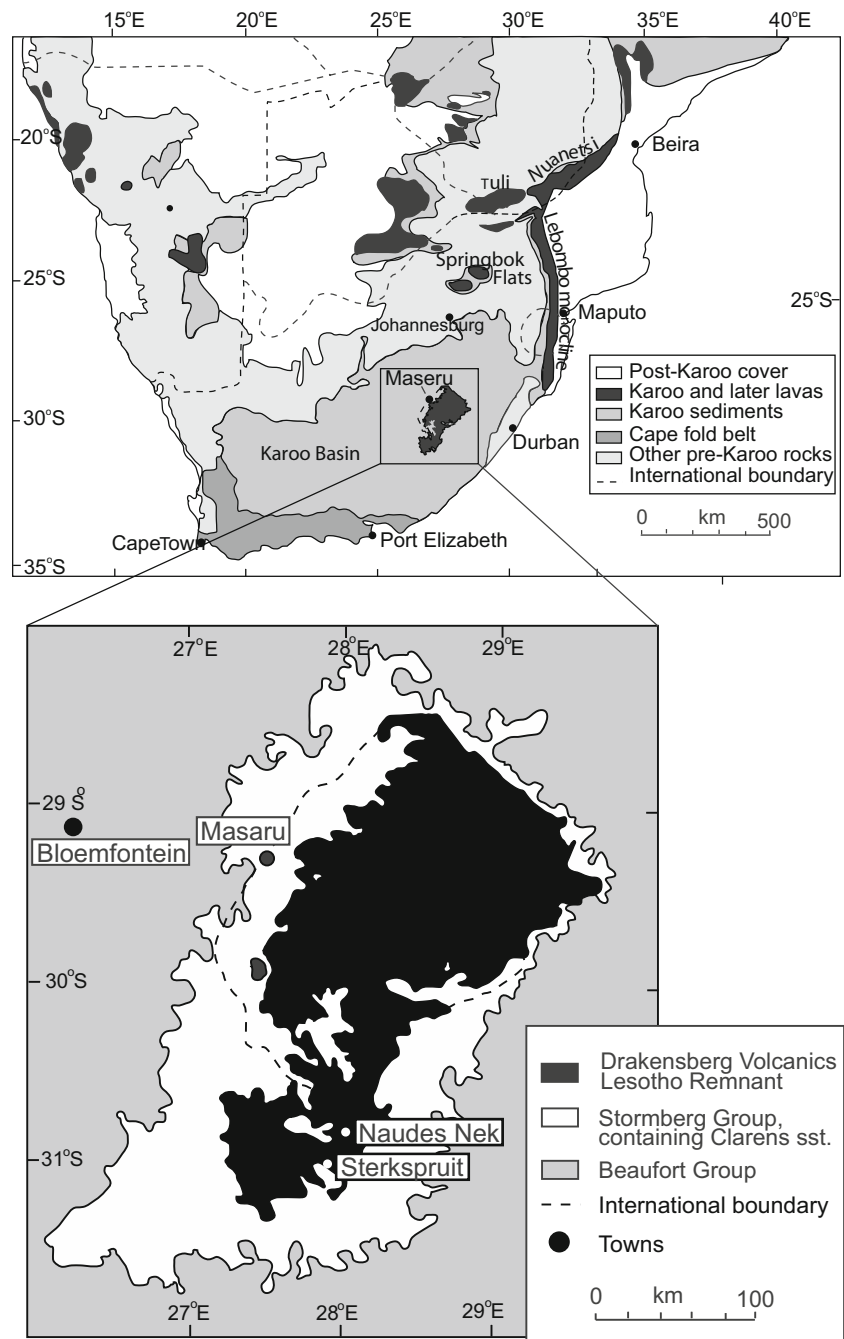
remnant contains a well-exposed horizontal sequence of sub-aerial basaltic lava flows, the Drakensberg Group, about 1.7 km thick. The sequence has been the subject of numerous studies relating to petrology, geochemical stratigraphy, palaeomagnetism, and duration of emplacement (e.g. van Zijl et al. 1962; Cox et al. 1967; Marsh and Eales 1984; Marsh et al. 1997; Duncan et al. 1997; Jourdan et al. 2007; Moulin et al. 2011; Moulin et al. 2017). In contrast, physical volcanological aspects of the Lesotho remnant and the Karoo province as a whole have received little attention with the few studies being focussed on phreatomagmatic complexes (near Sterkspruit, Fig. 1) in the Karoo sedimentary sequence immediately underlying the lava pile (Ross et al. 2005; Svensen et al. 2006; Holzforster 2007; McClintock et al. 2008a,b). There are no accounts of the physical volcanology of the lava flow sequence of the Lesotho remnant.

The 710-m-thick sequence of lavas documented in this study comprises the lower part of the Drakensberg Group as exposed along the Naude's Nek pass (Fig. 2; hereafter referred to as Naude's Nek), between 30.7806°S 28.0005°E (base) and 30.7614°S 28.0907°E (top), ENE of the village of Rhodes in the southern part of the Lesotho remnant, Eastern Cape (Figs. 1 and 2). This study was conducted in conjunction with a detailed palaeomagnetic investigation (see Moulin et al. 2011). In terms of the geochemical stratigraphy (Fig. 3a) established by Marsh et al. (1997), the sequence includes an informal unit, the Druid's Temple basalt (Fig. 3b), which overlies aeolian sandstones of the basal Clarens Formation, followed upwards by the Moshesh's Ford unit of the Barkly East Formation and the overlying Mafika Lisiu unit of the Lesotho Formation. The upper part of the Lesotho Formation (Maloti, Senqu and Mothae units) is not exposed. The section includes the basement contact, pillow lavas, siliciclastic sandstone layers, altered lava flow tops and lobes, toes and sheet lobes.

Methodology

Most observations of lava features were made in road cuts with minor use of stream sections and small quarries. The latter provided some degree of 3-D exposure. Altitudes and flow thicknesses used to construct the stratigraphic log of the section (Fig. 4) were derived by combining data from repeated measurements utilising an aneroid altimeter, GPS altimeters and a Jacob Staff with a Dumpy Level. Samples for whole-rock geochemical analysis were collected in road cuts and analysed for major and trace elements by wave-length dispersive X-ray Fluorescence spectrometry using a Philips 1480 spectrometer at Rhodes University, South Africa. During sample preparation care was taken to remove any amygdaloids. Duncan et al. (1984) provide full details of the analytical procedures.

Fig. 1 Map of distribution of erosional remnants of the Karoo Continental Flood Basalt Province, southern Africa. Inset, map of outcrops of the Drakensberg Group forming the Lesotho Remnant (after Eales et al. 1984)



Pāhoehoe flows and associated terminology

The identification of inflated pāhoehoe flow lobes in the field is derived from a tripartite internal structure, consisting of an upper crustal zone, a lava core and a basal crust. This is based upon the internal distribution of vesicles, crystallinity and joints (Self et al. 1998) with or without other internal and surface features, such as a pāhoehoe ropery surface.

The terminology used is that proposed by Thordarson and Self (1998; their Table 1). The products of an eruption are divided into three levels: flow field, lava flow and flow lobe.

As this study was carried out along a single traverse providing a 2D view of the lavas, lateral correlation of flows, and therefore identification of flow fields is not possible. However, flows have been grouped together as either compound flow (possibly hummocky pāhoehoe) or sheet lobes.

The term flow lobe is used to describe an individual unit of lava which is bounded top, bottom and sides by a glassy rind or selvage. In CFBPs, flow lobes can vary in size from 10^{-1} m (also called toes) to 10^2 m in thickness. Where a single flow lobe is a large-scale feature, i.e. wider than outcrop (10^2 to 10^3 m) and significantly wider and longer than it is thick

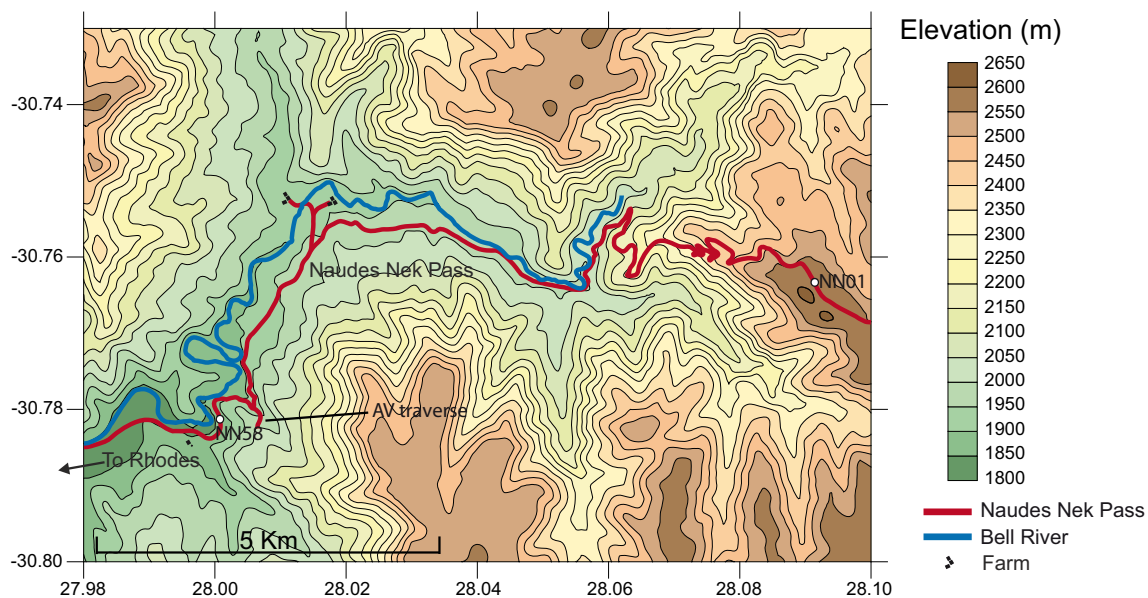


Fig. 2 Topographic map showing location of the Naude's Nek. The two sample locations mark the top and bottom of the section. AV traverse is the alternative valley traverse shown in Fig. 4 Topographic map is based

upon Shuttle Radar Topography Mission 2 (Rodriguez et al. 2005; Moulin et al. 2011)

(Thordarson and Self 1998), the term sheet flow lobe (shortened to sheet lobe) is used. We do not use the term simple flow (as suggested by Walker 1971); sheet lobe is used instead. However, we do use the term compound flow, especially where it has been used by previous authors. It describes multiple thin lobes and toes observed as part of a single lava flow.

Hummocky pāhoehoe is characterised by multiple flow-lobe tumuli on a sheet lobe or flow field. Flow-lobe tumuli are round, elongate or whale-back-shaped mounds 1–10 m high and > 5 m long, with axial clefts. They are formed by uneven inflation when the lava's passage is blocked, and it is easier for the lava to flow vertically than horizontally (Anderson et al. 2012). As the internal pressure increases the upper crustal zone of the pāhoehoe lobe is pushed up (Walker 1991). Thus, the upper crustal zone of the lobe dips at a much steeper angle than when it was originally emplaced. The fractures in the upper surface are infilled, either by squeeze-outs of

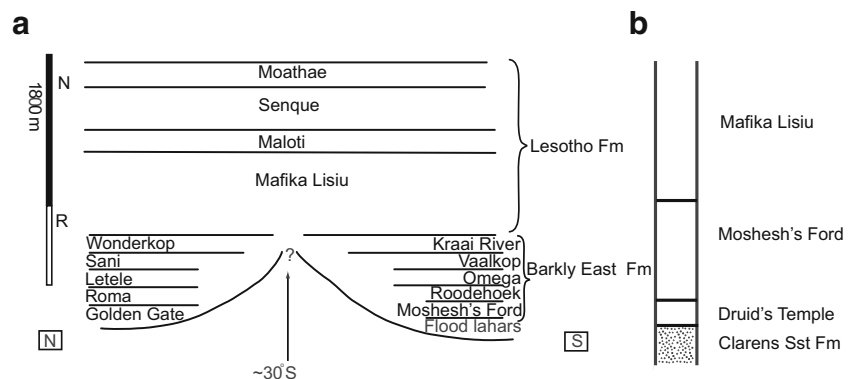
lava from below or by subsequent sheet lobes or sediment (Passey 2008).

Observations

Description of the Naude's Nek succession

The lavas along the Naude's Nek (Figs. 1, 2 and 4) are inflated pāhoehoe flows, consisting of small lobes and toes, tens of centimetres to a few metres thick, thin flow lobes up to 10 m thick, but at least 50 m wide, and sheet lobes 10–52 m thick. Where visible, all the lavas have the characteristic pāhoehoe tripartite division as defined by Self et al. 1998 which consist of (i) upper crust, showing increased vesicularity towards the upper surface and horizontal vesicular zones; (ii) a core which is massive, poorly vesicular, contains various degrees of

Fig. 3 **a** A schematic summary of the stratigraphy of the Drakensberg Group Lavas. Note that the Barkly East formation is formed of different units in the northern and southern parts of the outlier. **b** Sketch of the stratigraphy of the lavas along the Naude's Nek Pass



jointing and may show vesicle cylinders and horizontal vesicular sheets (HVS); and (iii) a basal crust which is vesicular, and often has pipe vesicles, which are mostly amygdaloidal.

Figure 4 summarises the sequence and gross characteristics of the flow lobes encountered in this study. Within the section there are 14 sheet lobes: 12 are between 10 and 24 m thick (flows NN34, NN32, NN27, NN22, NN21, NN20, NN18, NN17, NN16, NN15, NN14, NN06—see Fig. 4); one sheet lobe is 40 m thick (NN57); and one is unusually thick (approximately 52 m thick, NN35).

Basal contact

Throughout the Lesotho remnant there is an undisturbed, generally horizontal contact between the aeolian sandstone of the Clarens Formation and the lowermost basaltic flows of the Drakensberg Group. However, in detail there is modest topographic relief on the pre-volcanic palaeosurface resulting from the presence of dune forms and from erosion (e.g. at the base of the pass at Druid's Temple, 30.7806°S; 28.0583°E). Generally, in the southern part of the Lesotho Remnant, the lowermost flows immediately overlying the Clarens Formation are those of the Moshesh's Ford unit (Marsh and Eales 1984), but at the base of the Naude's Nek this unit is underlain by an informal unit, the Druid's Temple Flow (Fig. 3b), which has demonstrably ponded in a topographic hollow.

Sedimentary layers

Thin, discontinuous sedimentary deposits are interbedded with the lowermost lavas throughout the Lesotho remnant. At Naude's Nek several sedimentary layers occur between the base of the lavas (1866 m) and an altitude of 2075 m (Fig. 4). They are dominantly fine-grained, quartz-rich sandstones and minor siltstones with variable amounts of clays and volcanoclastic clasts (plagioclase, pyroxene, devitrified glass; Moulin et al. 2011). Many of the sandstones resemble Clarens Formation (Fig. 3b) sandstone and may have a dominantly distal derivation (originating from the source of the Clarens Formation, far to the west), or of local derivation, having formed by erosion of unconsolidated Clarens deposits projecting above the thickening lava pile. Those sandstones with a volcanic component are probably locally derived. The lowermost 30–40-cm-thick siliciclastic deposit at 1880 m altitude underlies a thin sequence of pillow lavas and presumably accumulated in a pond or lake. At 2045 m altitude, reddish sandstone partially covers a flow and has infilled gashes and clefts in a tumulus that penetrate several metres into the underlying lava. The youngest sandstone horizon at 2075 m altitude probably represents the time by which lava had covered all of the Clarens source material in the Karoo basin.

Pillow lavas

A 2-m-thick sequence of pillow lavas associated with a sandstone interbed occurs at 1880 m altitude at the base of the Moshesh's Ford unit, just above the contact with the Clarens Formation (Fig. 4). The pillow package is characterised by substantial alteration with devitrification of the glassy pillow rinds and extensive alteration and zeolitization of the hyaloclastite between the pillows. The pillow zone grades upwards into a 1.5-m-thick zone of small, altered amygdaloidal lobes or toes which in turn passes abruptly upwards into a massive, 40-m-thick sheet lobe, of which the lower 10 m displays closely-spaced hackly and fanned joints.

Boles and hydrothermally altered horizons.

Boles are altered, weathered material found between sheet lobes or forming a weathered lava flow top (Rajendran et al. 1996; Sayyed 2014). We found seven boles in this section at altitudes of 2050, 2155, 2213, 2309, 2349, 2500 and 2516 m (Fig. 4). The boles are reddish in colour and up to 50 cm thick. Some are extensive (extending along flow contacts beyond the exposure of the outcrop > 50 m) but others form only small pockets in undulating flow tops. It is likely that the boles are weathered flow tops or palaeosols that formed in-situ, or in small depressions where thin sedimentary deposits accumulated (Moulin et al. 2011).

Three hydrothermally altered flow tops occur in the section. At 2128 m altitude, an approximately 2-m-thick alteration horizon occurs across the contact between two flows (Fig. 5). The altered part of the lower flow has the typical vesicular character of an upper crustal zone and the alteration has affected the thin basal crust and some of the core of the upper flow. The alteration front stops abruptly and the remaining core of the upper flow is blocky and jointed. The flow boundary can be identified by the occurrence of pipe vesicles in the basal crust of the upper flow. This suggests that the alteration occurred after the emplacement of the upper lava. It is probable that the heat of the upper lava flow released fluids from the lower lava lobes, or from thin sediments between the lavas. These fluids circulated through both flows forming an 'autoclave' (Martine Gérard, pers. comm. 2006), resulting in alteration of the basalt across the flow boundary. Two other hydrothermally altered flow tops occur at 2380 and 2460 m.

Segregation features

Horizontal vesicular sheets (HVS; Fig. 6a) and vesicle cylinders (Fig. 6b) are a relatively common feature of the lavas in this section. However, with one exception at ~2498 m altitude, they are restricted to lobes that exceed 5 m thick (Fig. 4). We have found HVS only in the upper part of the section

◀ **Fig. 4** Stratigraphic log of the volcanic sequence along Naude's Nek and Bell River. The lack of road-side exposure between 1924 and 2000 m is alleviated by an 'alternative valley section' (AV—Fig. 2) logged up a side stream, starting on the road (at 30.779217°S 28.053833°E). Elevation is in metres above sea level. NN01 etc. are sample locations taken for palaeomagnetic studies, as published in Moulin et al. (2011). *T* Tumuli defined by axial cleft and dipping upper crustal zone, *SL* sheet lobe, *BBJK* Bobbejaan Kop, brackets define hummocky pāhoehoe. In hummocky pāhoehoe sections, those with multiple thin flows are represented schematically on the log

above 2068 m altitude, but this might simply be a function of the poorer exposures along the Bell River. The HVS are sometimes amygdaloidal, but are mostly free of secondary minerals. In some lobes only vesicle cylinders are observed, without HVS (e.g. NN19, Fig. 6b). In two lobes, HVS appear to occur without vesicle cylinders (2413 and 2475 m altitude).

Table 1 compares XRF analyses of segregation features (more evolved material) and their associated host in four flow lobes (NN19, NN34, NN35, NN44). Samples of the host were collected from the amygdale-free core of each lobe close to the associated HVS. In all cases the analysed HVSs are clearly differentiated relative to their hosts, as indicated by enrichment of incompatible elements Ti, P, K, Nb, Zr, Y, Rb and depleted in compatible elements, such as Mg, Ni, Cr. This is consistent with the HVSs being formed from the concentration of differentiated interstitial liquids in sheet-like zones

during crystallisation of the lobes, as has been inferred for other CFBPs (Greenough and Dostal 1992; Hartley and Thordarson 2009).

In contrast, in the single lobe with only vesicle cylinders (NN19), the host and basaltic cylinder fill have identical compositions in terms of incompatible elements, and are only slightly different in differentiation-sensitive compatible elements, such as Mg, N, and Cr.

Hummocky Pāhoehoe

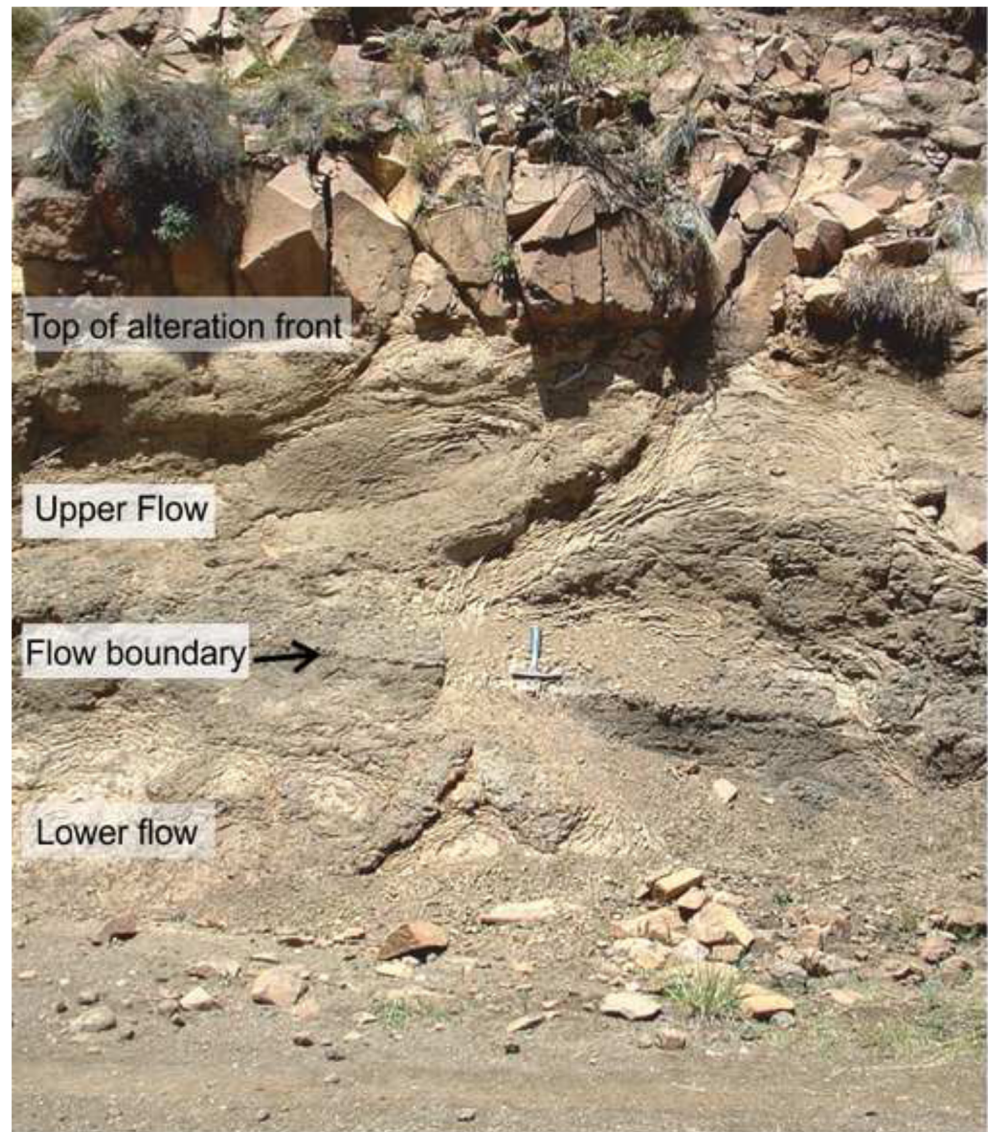
The lobes observed have convex upper surfaces. In some localities, lobes have relatively flat upper surfaces with only the sides dipping, whereas in other lobes the whole of the upper surface dips steeply (Figs. 7 and 8). The steeply dipping nature and therefore uneven inflation of these features means that lobes have variable thicknesses laterally (from decimetres upwards). We suggest that these lobes are flow-lobe tumuli (Figs. 7, 8 and 9) and are best represented by the flows at 2517, 2482, 2479, 2206, 2164, 2045 and 2056 m altitude.

In addition, some lobes have deep v-shaped clefts through their upper crustal zones (Fig. 9) clearly demonstrating these are flow-lobe tumuli. These clefts are infilled with lava, hereafter called lava fingers following Duraiswami et al. (2005) and, at one locality by sediment. The lava fingers are up to 1 m

Table 1 Composition of horizontal vesicular sheets (HVS), vesicle cylinder, and host lava

	NN19 Host	NN19-VC Vesicle cylinder	NN19-VC Vesicle cylinder	NN34 Host	NN34-S HVS	NN34-S HVS	NN35 Host	NN35-S HVS	NN44 Host	NN44-S HVS
SiO ₂	50.41	51.77	54.22	51.91	56.47	56.4	52.69	58.62	51.96	57.71
TiO ₂	0.93	0.89	0.87	0.829	2.85	2.42	0.91	1.84	1.02	1.86
Al ₂ O ₃	15.4	15.74	14.35	15.65	11.74	11.55	15.32	12.63	15.7	11.58
FeO	10.69	10.13	9.75	9.77	14.55	14.03	9.9	13.21	10.09	13.63
MnO	0.18	0.17	0.19	0.18	0.17	0.27	0.18	0.18	0.18	0.26
MgO	8.3	7.93	7.23	8.25	3.22	4.44	7.2	2.91	7.08	3.79
CaO	11.12	10.74	10.52	10.67	6.09	6.69	11.2	5.81	10.95	6.11
Na ₂ O	2.42	2.09	2.31	2.13	2.72	2.41	1.91	2	2.21	3.04
K ₂ O	0.41	0.39	0.43	0.49	1.73	1.35	0.53	2.17	0.62	1.61
P ₂ O ₅	0.15	0.14	0.14	0.13	0.46	0.43	0.16	0.65	0.20	0.41
Nb	6.1	5.3	5.6	5	18.2	17	5.6	24.1	9.2	22.4
Zr	82	81	78	65	228	216	79	304	89	195
Y	24.6	24.2	23.6	21.7	62.5	59.6	26.3	84.5	27	48.6
Sr	172	172	166	174	167	157	186	176	221	171
Rb	3.3	3.6	5	9.2	35	25	9.5	45	11.4	32
Zn	88	84	82	75	145	139	81	116	78	143
Cu	74	74	87	81	164	121	83	89	102	108
Ni	102	96	84	100	28	31	84	8	78	23
Cr	297	280	241	330	10	10	397	4	219	24
V	234	228	233	225	441	389	247	56	239	314

Fig. 5 Flow boundary with altered basalt either side, probably formed by the circulation of hot fluids (autoclave) induced by the emplacement of the upper flow. 2128 m and 30.7551°S 20.6317°E



wide, and penetrate up to 3 m into the lobe from its upper surface (Fig. 9). The lava fingers have chilled margins and are texturally distinct, being hyalopilitic and amygdaloidal. In some wide lava fingers, pipe vesicles have developed perpendicular to the lava finger contacts and curve upwards in the interior of the lava finger. In the narrow termination of the lava finger, the cleft may be infilled by secondary zeolite or a zeolite-cemented basalt breccia (Fig. 10). Some of the lava fingers occupy a single cleft but others are components of intersecting cleft systems forming ‘triple junctions’ in plan-view. There are two possible origins for the lava fingers: (a) basalt lava from within the flow-lobe tumulus, or its associated flow, flowed into the cleft during the development of a squeeze-up (endogenous origin); or (b) lava that flowed into the clefts from an overlying, later lobe (exogenous origin). The observation at flow NN38 (2056 m; Fig. 9) of a direct

connection between the lava finger and the overlying lobe suggests that the lava fingers represent clefts filled from an overlying lobe. The incomplete filling of the cleft at its base (Fig. 10) is also consistent with this hypothesis.

Geochemical analysis also offers the potential to distinguish between endogenous or exogenous origins of lava filling clefts in flow-lobe tumuli. At 2481 m altitude samples of three thick lava fingers (NN12-V1, V2, V3), their host flow-lobe tumulus (NN12), and the overlying lobe (NN12-O) were analysed. The samples were analysed using XRF and the results presented in Table 2. If the overlying lobe had the same composition as the lava in the clefts, but differed from the host, this would be strong evidence for an exogenous origin for the lava fingers. From Table 2 it is clear that the lobes and lava fingers have identical compositions, especially when immobile incompatible and compatible elements are compared.

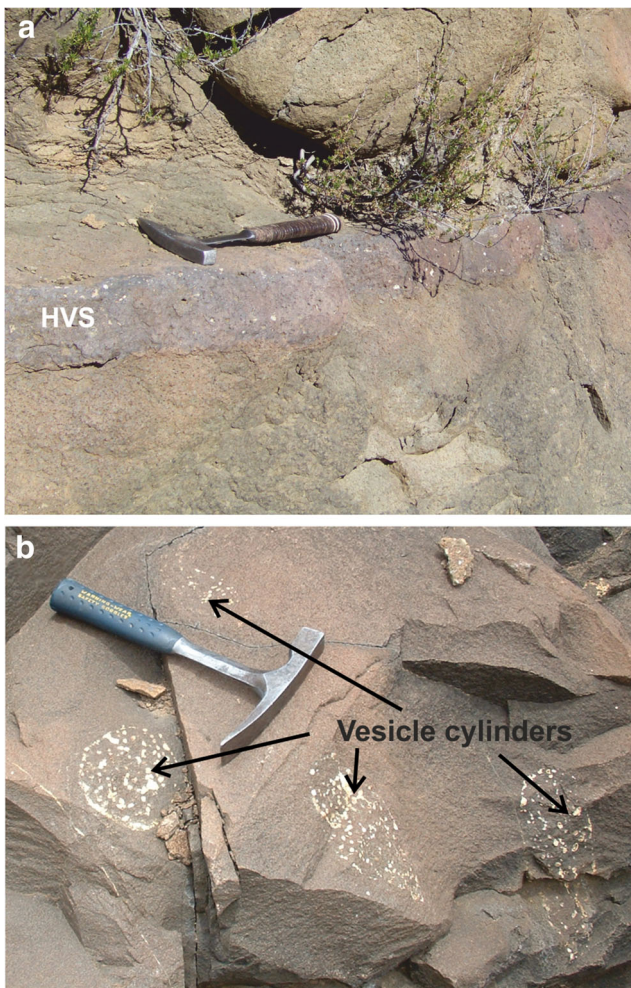


Fig. 6 **a** Horizontal vesicular sheet (HVS) in NN34. 2130 m and 30.75449°S; 28.06330°E. **b** Plan view of amygdaloidal vesicle cylinders. 2355 m and 30.75398°S; 28.07353°E

These data indicate that both lobes were from the same magma batch and in this specific instance geochemistry alone cannot resolve the origin of the lava fingers.

The abundance of flow-lobe tumuli and smaller flow lobes results in a complex 3-D lava architecture at several places along the Naude's Nek section (e.g. at Bobbejaankop 2230–



Fig. 7 Steeply dipping upper crust of a flow-lobe tumuli

2293 m altitude and 30.77819°S 28.06458°E). Such sections are challenging to log and it is difficult to recognise the correct chronological sequence. However, 3-D exposures in quarries and on hairpin bends help to clarify the complexities of the lava architecture.

For example, in Fig. 11 (~2065 m altitude), a large lobe appears to occur beneath a pile of smaller lobes, but when the larger lobe is traced carefully it outcrops again further up the section and engulfs other smaller lobes and toes and is, therefore, younger. Hence, the careful use of localities with complex 3-D exposures is important to avoid misidentification of stratigraphy.

In the back wall of a small quarry next to the road (2470 m, 30.760167°S 028.08125°E), approximately 1 m above the quarry floor, the upper crustal zone of a sheet lobe is well exposed in cross-section (Fig. 12) and clearly displays an amygdaloidal upper crust. In the side wall of the quarry, the same upper crustal zone can be seen dipping towards the back of the quarry. The upper crustal zone of this lobe is approximately 5 m higher, where it is exposed on the road side, than in the back of the quarry. This is an excellent example that demonstrates the hummocky and complex nature of pāhoehoe flows lobes.

Discussion

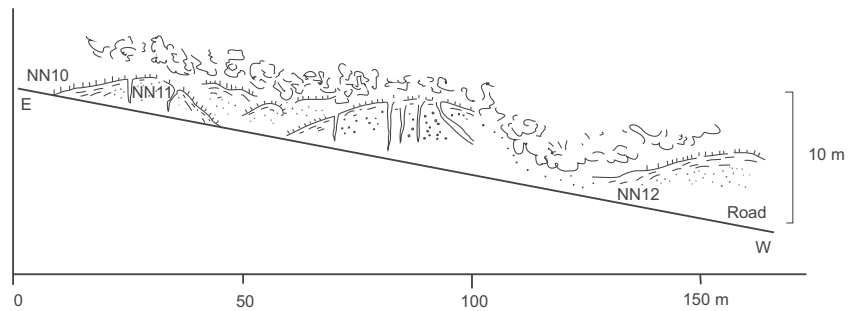
Emplacement of lava flows

Emplacement time for these flows is difficult to measure, but some estimates can be made. For example, Hon et al. (1994) proposed an equation to estimate the time required for the upper crust of a pāhoehoe flow to form (i.e. the length of time the lobe was actively inflating) using observations of upper crustal zones of active inflating lava flows at Kilauea (Hawai'i). Hon et al. (1994) state that

$$t = 164.8C^2 \quad (1)$$

where t is the time in hours, 164.8 is an empirically determined constant and C is the upper crust thickness in metres. Assuming similar cooling rates for Hawaiian and Karoo lavas, this equation yields emplacement times of 11 to 27 days for upper crusts of 1.25 to 2 m thick in the Karoo lavas. We note that there may be differences between the cooling rates of Hawai'i lavas and the cooling rates in the Karoo lavas, caused by factors such as annual rainfall (likely to be much higher in Hawai'i than the semi-arid Karoo at 182 Ma), and differing thermal properties, such as diffusivity, heat capacity, and latent heat of crystallisation. At present, though this is the only tool available for estimating lava emplacement rates.

Fig. 8 Sketch showing a series of tumuli with axial cleft at approximately 2480 m above sea level



Pāhoehoe: scale and features

CFBP eruptions are orders of magnitude larger than witnessed monogenetic basaltic eruptions but the volcanological features observed are similar, and ‘scale-up’ with flow size (Thordarson and Self 1998). However, sheet lobes > 10 m thick are very rare in modern systems (flows up to 25 m thick are observed in the active volcanic zone of Iceland; Thordarson, 2017 pers. comm.), but are relatively common in CFBPs. The volcanological features observed along the Naude’s Nek concur with these observations and generally span the same size range as that of modern basaltic pāhoehoe lobes.



Fig. 9 Cleft in the upper crust of a flow-lobe tumulus, infilled by the subsequent flow, note hammer for scale. 2056 m and 30.757583°S 28.059194°E

Many of the lava lobes encountered in the Naude’s Nek section (Fig. 4) are relatively thin (decimetres to 10 m), and have convex upper surfaces (Fig. 7). Restricted exposure on the section presents difficulties in determining the lateral



Fig. 10 Narrow termination of an axial cleft in a tumulus, partially infilled by the subsequent flow-lobe. Secondary mineralization has infilled the vesicles within the lobe and the end of the cleft which was too thin to be filled with lava. 2470 m and 30.76000°S; 28.08335°E

Table 2 Composition of lava in clefts and their host tumulus

	NN12-H Host	NN12-O Overlying flow	NN12-V1 Vein	NN12-V2 Vein	NN12-V3 Vein
SiO ₂	52.34	52.41	53.96	53.69	54.72
TiO ₂	0.89	0.85	0.87	0.87	0.89
Al ₂ O ₃	15.31	15.51	14.68	15.08	14.68
FeO	10.27	10.15	10.1	9.87	9.58
MnO	0.17	0.15	0.17	0.15	0.18
MgO	7.32	7.22	7.21	7.08	7.08
CaO	10.57	10.33	8.86	9.46	8.9
Na ₂ O	2.29	2.41	3.02	3.03	3.14
K ₂ O	0.68	0.82	0.96	0.61	0.68
P ₂ O ₅	0.15	0.15	0.16	0.15	0.16
Nb	8.3	8.1	7.6	7.7	8.1
Zr	94	92	94	91	96
Y	24.4	26.1	24.2	23.4	24.2
Sr	180	190	105	79	154
Rb	10.4	15.1	17	11.2	11.8
Zn	85	84	85	82	86
Cu	82	83	78	80	51
Ni	84	87	78	72	79
Co	44	44	43	43	45
Cr	260	251	249	242	250
V	238	235	255	246	264

extent of lava lobes (Fig. 11). Given that many lobes and toes are only a few metres thick (Fig. 4) the lateral extent is likely to be of the order of only 10s to 100s of metres. However, there are 14 lobes (SL on Fig. 4) that are more than 10 m thick and these have been classified as sheet lobes. Tracing these sheet lobes laterally is difficult due to the poor exposure, but the thickest, a 52-m-thick lobe (NN35), is visible for a lateral distance of about 1.5 km. These 14 sheet lobes make up 314 m of the section (45%). The bulk of the thick sheet lobes occur in two groups (Fig. 4) at respective altitudes 2085–2180 m and 2335–2460 m, the others being either discrete individual sheet lobes or occurring in groups of two sheet lobes within a stack compound lobes. This suggests that there were two periods of extended and relatively high lava supply allowing multiple sheet lobes to grow to considerable thicknesses (> 10 m).

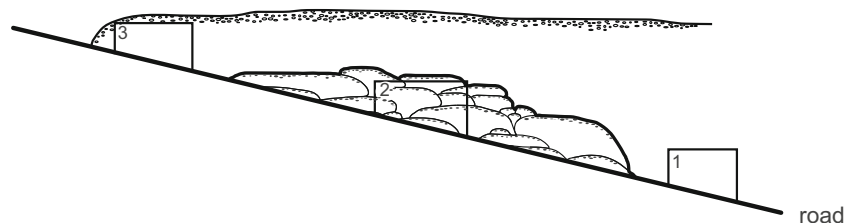


Fig. 11 Cartoon showing stratigraphic complexities that can occur when a pile of small lobes is engulfed by a larger sheet lobe. An example of this is seen at ~2065 m. If, on traversing the road, sequential observations are

The individual and double sheet lobes within compound flows indicate one or two eruptions with extended and higher lava supply rates, before returning to a lower supply rate.

Research in the Miocene Columbia River Basalt Group, NW USA, on the Roza Member, demonstrates that sheet lobe thickness does not correlate with distance from vent (Thordarson and Self 1998). Thus, these 14 thick sheet lobes must be the result of periods of higher and more prolonged lava supply rate rather than their thicker nature being the result of proximity to the vent.

Flow-lobe tumuli with axial clefts (Fig. 9) are found in several locations. They are indicative of hummocky pāhoehoe (Fig. 4) flow fields. There are seven discreet packages of lava units in the Naude's Nek which can be classified as compound hummocky pāhoehoe flow fields. These make up approximately 370 m (50%) of the section (Fig. 4). Thick sheet lobes and compound hummocky flow fields therefore make up a similar proportion of the observed section, and again indicate significant variability in the emplacement style.

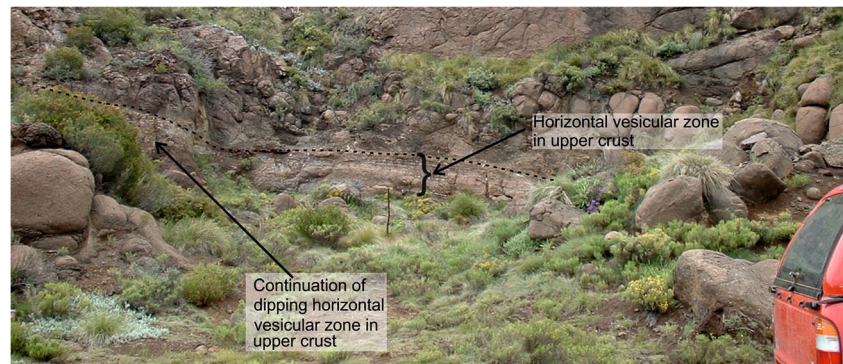
Pipe vesicles are found in the basal crust of lobes. They are normally vertical or sub-vertical, possibly indicating local flow direction. Pipe vesicles found in the basal crust of lobes which were emplaced into the clefts in flow-lobe tumuli are curved upwards and occur on both sides of the cleft giving the appearance of two basal crusts (Fig. 9).

Implications of identification of flow-lobe tumuli

The presence or absence of flow-lobe tumuli within a CFBP provides intriguing questions: what causes flow-lobe tumuli to form in some CFBPs but not others, and what does their occurrence tell us about the lobes they are found in? Flow-lobe tumuli typically develop on surfaces with irregular topography (decimetres to metres in scale), slopes of 1–2°, and at a point in the flow where there is either a low lava supply rate (of the order of 10^{-2} to 10^{-5} m³/s) or a disrupted or discontinuous supply rate (Hon et al. 1994; Rossi and Gudmundsson 1996; Self et al. 1998). The frequent occurrence of small pāhoehoe lobes and toes in the Naude's Nek section (Fig. 4) could have provided the topographically-rough surface that allows flow-lobe tumulus formation.

confined to the three boxes then the thick lobe in box 3 would be inferred to be younger than the packet of small lobes whereas it is part of a lobe which is older

Fig. 12 Sheet lobe dipping into the rock face. Horizontal vesicular zone of upper crust is picked out in white amygdales visible as semi-horizontal lines towards the base of the quarry. This is continued in the left hand side of the quarry wall at 2470 m and 30.760167°S 28.08125°E



In modern basaltic volcanic regions, hummocky pāhoehoe terrains and their flow-lobe tumuli are typically found at medial to distal (from source) parts of sheet lobes where, in addition to a low supply rate, the local lava pressure is high (Rossi and Gudmundsson 1996; Mattsson and Skuldsson 2005); both conditions are necessary for the formation of flow-lobe tumuli. If the work of Walker (1991), Rossi and Gudmundsson (1996) and Mattsson and Skuldsson (2005), which was carried out on small basaltic systems, is also applicable to a flood basalt systems (which seems probable; see Thordarson and Self 1998), then the occurrence of flow-lobe tumuli may indicate that those in the Naude's Nek section developed in a zone medial and distal to the source.

As CFBPs are often highly eroded, poorly exposed and lacking exposed volcanic vents, it is often impossible to know whether the area of study is proximal or distal to source. Also, if the margin of the province is not visible then it is difficult to evaluate the erupted volumes. However, the identification of flow-lobe tumuli within compound flows provides a means to identify medial and distal parts of CFBP sheet lobes. With adequate mapping the location of flow-lobe tumuli may help the identification of postulated vent systems.

Other CFBP with and without flow-lobe tumuli

In the Thakurvadi and Bushe Formations of the Deccan CFBP, Duraiswami et al. (2001, 2002, 2004) and Bondre et al. (2004) have described accumulations of flow-lobe tumuli with convex upper surfaces, axial clefts and associated small lobes and toes. These are analogous to the observations from Naude's Nek presented here (Figs. 7 and 8).

In the Paraná part of the Paraná-Etendeka CFBP, Waichel et al. (2006) have identified hummocky pāhoehoe, thin inflated lobes (decimetres to a few metres) and toes, segregation features, and flow-lobe tumuli with axial clefts. They also describe the thicker sheet lobes up to 30 m thick, as observed in the Naude's Nek. Similarly, El Hachimi et al. (2011) record compound flows, sections of thin but inflated pāhoehoe lobes and toes with limited lateral extent (10–100 m), and flow-lobe tumuli with axial clefts containing squeeze ups in the Argana

Basin, Morocco, Central Atlantic Magmatic Province. Hence, the observations made at Naude's Nek are not unique, and there is clearly a commonality of emplacement styles between this and some other studied CFBPs.

Flow-lobe tumuli are absent from compound flows in some CFBPs. In the Steens Basalt, USA, Bondre and Hart (2008); Bondre pers. comm. (2017) and Camp et al. (2013) have detailed many compound flows but have made no mention of flow-lobe tumuli. Similarly, in the Paleogene Faroe Island Basalt Group (North Atlantic Igneous Province) flow-lobe tumuli are seemingly absent (Passey and Bell 2007; Passey pers. comm. 2017).

Along Matheran Ghat (Deccan CFBP, 45 km east of Mumbai), Jay (2005) logged a ~550 m vertical thickness of basalt containing the entire thickness of the Thakurvadi Formation (Fm), but observed no flow-lobe tumuli. This is perhaps surprising, considering that flow-lobe tumuli have been found in other parts of the Thakurvadi Fm. and that the section is dominated by lobes and toes that would have provided an uneven topography ideal for flow-lobe tumuli formation.

What does the presence and absence of flow-lobe tumuli tell us about CFBP emplacement?

The simplest explanation for the presence or absence of tumuli in a CFBP might simply be that CFBPs have not been well-logged and studied to a similar level of detail in all areas, so the presence of flow-lobe tumuli may have been overlooked. However, this is unlikely, given that in the areas where they are found they are common and easily recognisable. Also, in many of the studies described above, the level of detail recorded was easily sufficient for flow-lobe tumuli identification if they had been present. This suggests that the variation in flow-lobe tumuli presence is a real feature of CFBPs.

Flow-lobe tumuli formation does not seem to be dependent on magma chemistry, which can change the lava's physical properties, as flow-lobe tumuli are absent in one part of the (geochemically defined) Thakurvadi Fm (Deccan CFBP) but common in another (e.g. Duraiswami et al. 2004; Jay 2005).

Evidence from modern volcanic systems suggests instead that it is the rate of lava supply that controls the formation of flow-lobe tumuli and that this is related to distance from vent (Hon et al. 1994; Rossi and Gudmundsson 1996). For example, as lobes develop, they initially move rapidly away from the vent. The velocity slows further from the vent as the lobe spreads out, growing laterally as well as longitudinally (Hon et al. 1994). Once the lava supply rate drops low enough (10^{-2} – 10^{-5} m³/s; Rossi and Gudmundsson 1996), depressions or temporary reductions in lava supply can lead to blockages, and hence flow-lobe tumuli formation. In addition, at these low supply rates, the upper crust of the lobe will rapidly start to thicken thus limiting further growth of the lobe (Hon et al. 1994); hence, this is why flow-lobe tumuli form in the parts of lobes medial and distal to vent. However, the length of a lobe and therefore the sections that are ‘medial or distal to source’ are specific to each individual lobe and are dependent on the lava supply rate of each eruptive event. A small eruption with a total flow length of only 5 km will have flow-lobe tumuli much closer to the vent than a larger volume eruption, in which 5 km downflow is still classed as ‘proximal’ to the vent.

There are few studies defining the limits of lava supply rate required for flow-lobe tumuli formation. Rossi and Gudmundsson (1996) calculated that the lava supply rate at the location of flow-lobe tumulus formation needs to drop to 10^{-2} – 10^{-5} m³/s for a tumulus to form, but other data for lava supply rate in tumuli formation could not be found in the literature. The effusion rate (the volumetric rate that lava is extruded from the vent) and the mean output rate (the total erupted volume divided by the duration of the eruption) are the rates that are often quoted in text (e.g. Anderson et al. 2012), but these are not the rates upon which flow-lobe tumuli formation depend. Instead, these form under a local effusion rate which is lower than the total (vent leaving) rate (Rossi and Gudmundsson 1996) as the flux has been partitioned amongst multiple units. This is an interesting avenue for future research that would provide data that could be applied to the understanding of the growth and development of CFBPs.

What do observations from Naude’s Nek tell us about CFBP development and growth?

The section studied here shows considerable variations in lava architecture, with ~50% of the ~710 m traverse being thick sheet lobes and ~50% hummocky pāhoehoe. We suggest that the sections of the traverse which display hummocky pāhoehoe were characterised by low lava supply rates and were therefore medial or distal to source. The thick sheet lobes had a supply rate greater than that required to form flow-lobe tumuli and a lava supply period long enough to form a flow up to 52 m thick.

Like the thick sheet lobes in Naude’s Nek, we suggest that the Thakurvadi Fm. lavas (Deccan CFBP) of Matheran Ghat

that do not show flow-lobe tumuli had a lava supply rate high enough ($> 10^{-2}$ – 10^{-5} m³/s; Rossi and Gudmundsson 1996) to overcome the uneven surface created by thin lobes and toes so that blockages leading to flow-lobe tumuli creation did not occur. However, the lava supply period was not sufficient to inflate the lobes to the great thicknesses seen in the sheet lobes forming ~50% of the Naude’s Nek and other parts of the Deccan CFBP. These Thakurvadi Fm flows (Matheran Ghat) are similar to the pāhoehoe observed by Hon et al. (1994) which flowed over uneven surfaces with flow rates of 1–2 m³/s and which also never formed flow-lobe tumuli. Lavas from other locations in the Thakurvadi Fm. in which flow-lobe tumuli formed must have had a lower flow rate, and therefore were more easily blocked, suggesting they were more distal from source.

It has been suggested that compound flows are indicative of proximity to source and sheet lobes indicative of distal locations (Deshmukh 1988; Viereck et al. 1988; Leshner et al. 1999; El Hachimi et al. 2011). However, we argue that this is incorrect: the thickness of inflated flows is determined by the length of time that lava can continuously flow through a lobe and inflate it, not how close it is to the vent. So the presence of a series of thin compound flows or thick sheet lobes do not suggest anything about proximity to vent, just the length of time the lava was inflating for. However, the presence or absence of flow-lobe tumuli within a compound flow can tell us whether a flow is proximal or distal to source.

Segregation features

Segregation features form from gas filter pressing of residual melt and are enriched in incompatible elements (Goff 1996; Rogan et al. 1996). They are recognisable as vertical and horizontal vesicular or amygdaloidal cylinders or sheets (vesicle cylinders (Fig. 6b) and horizontal vesicular sheets (Fig. 6a; HVS)) within the core of a lobe. Often the vesicle cylinders feed into the horizontal sheets. In two lobes (2413 and 2475 m altitude), HVS appear to occur without vesicle cylinders. This is curious as vesicle cylinders and HVSs are widely regarded as being cogenetic on the basis of field evidence (i.e. they visibly interconnect), and geochemical evidence (i.e. they are both filled with residuum (Rogan et al. 1996; Self et al. 1997)). One HVS (2068 m altitude), associated with many vesicle cylinders, is unusual in that it is highly undulatory. In one lobe which has only vesicle cylinders, the host and cylinders have almost identical compositions in terms of incompatible elements and is only slightly different in differentiation sensitive compatible elements such as Mg, Cr and Ni. The geochemical and field observations from this example (NN19) in the Naude’s Nek section suggest that in this case the vesicle cylinders are not formed from residual liquid and may have been formed by a different process. We suggest that

further detailed geochemical studies may be required to identify such processes.

Palaeoenvironmental influences and settings

The pillow lavas and associated closely-spaced hackly jointing in the overlying sheet lobe at the base of the section (1880 m altitude) demonstrate the presence of standing water during emplacement of the earliest lava. Similar localised accumulations of pillow lavas and thin horizons of sedimentary rocks of limited lateral extent occur at several places amongst the lowermost lavas in the southern part of the Lesotho remnant (Lock et al., 1974; McClintock et al., 2008a), but elsewhere are extremely rare in the Karoo lava sequences. This, together with the scattered occurrences of thin fluvial sedimentary interbeds, indicates the presence of scattered ephemeral ponds or lakes into which some detrital sediments accumulated and lavas flowed. This is consistent with the sedimentological evidence from the upper part of the Clarens Formation that indicates the existence of sheet floods, wadis and dune systems (Smith 1990).

Conclusions

We have produced the first description of the physical volcanology of the Lesotho remnant of the Karoo CFBP. The ~710-m-thick Naude's Nek section of the Karoo CFBP is composed of basaltic, inflated pāhoehoe. Approximately 50% of the section is relatively thin lobes and toes, compound flows, and 50% is comprised of 14 sheet lobes, each between 10 and 52 m thick. Lobes with steeply dipping convex upper surfaces containing deep gashes and axial clefts are seen in some compound flows in Naude's Nek, and we interpret these as flow-lobe tumuli.

Hummocky pāhoehoe forms where lava with a low supply rate encounters an uneven surface causing blockages which form flow-lobe tumuli. If low lava supply rates continue, hummocky pāhoehoe is self-perpetuating, constantly providing an uneven surface to obstruct the next lava lobe.

Thick sheet lobes require a lava supply rate high enough to overcome any obstacles that could cause flow-lobe tumuli formation, and a prolonged supply rate, long enough to inflate a flow to > 10 m thick. The proximity of a flow to the vent is not relevant.

The majority of the thick sheet lobes, in the section logged, are in two packages, approximately 100 and 150 m thick. This indicates that there were two prolonged periods of extended, higher lava supply rate, capable of producing thick sheet lobes. The other sheet lobes are formed individually or as groups of two within compound flows, providing evidence for brief increases in lava supply rate followed by a return to a lower level.

The colocation of thin compound flows, tumuli-bearing hummocky pāhoehoe and thick sheet lobes at Naude's Neck

imply considerable variations in lava supply rates and eruption duration. This is reinforced by the occurrence of weathering horizons within the stack of lavas which indicate hiatuses in the emplacement of the lava (which agrees with the relatively short emplacement times calculated from (1) for individual lava flows). Naude's Nek demonstrates that the Karoo, and probably CFBPs in general, have heterogeneous eruptive histories, and that their vertical accretion includes many styles of volcanism, as well as alteration of volcanic products. Some aspects of the environmental changes and discrete episodes of mass extinction in the Pliensbachian-Toarcian could be linked to these heterogeneous eruptive histories (Moulin et al. 2017).

Compound flows do not indicate a flow's proximity to vent, as the thickness of a flow is determined by the length of time it continues to inflate for. However, the presence or absence of flow-lobe tumuli in compound flows can be used as an indicator that a lobe is proximal or distal to source. The entire Thakurvadi Formation (Deccan CFBP; geochemically defined) has no flow-lobe tumuli in one location, but they are found in an area thought to be distal to source. The presence of flow-lobe tumuli helps to confirm they are distal at a particular location. More spatial studies of flow-lobe tumuli in both modern and ancient lava flows could be used to test this hypothesis.

A small eruption with a total flow length of only 5 km will have flow-lobe tumuli much closer to the vent than a larger volume eruption, in which 5 km downflow is still classed as 'proximal' to the vent. Therefore the presence of flow-lobe tumuli cannot give a quantitative measure of distance from vent, only a measure of their relative position within their flow. In addition, numerous flow-lobe tumuli should be mapped in a similar location but at different stratigraphic levels to be sure that an area is distal from source. A single short flow could give anomalous results.

Given that continental flood basalt sequences, like the Karoo, represent extremely voluminous eruptions often with little or no evidence of the source of the eruptions a revised approach to assessing proximity to vent will hopefully be welcomed.

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